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MAPPING THE POTENTIAL SPREAD OF THE ZEBRA MUSSEL (DREISSENA POLYMORPHA) IN ONTARIO

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Summary

The European zebra mussel, (*Dreissena polymorpha*) is now firmly established in the lower Great Lakes and in isolated locations in the upper Great Lakes. Dispersal is aided by high fecundity, a planktonic larval stage, and ability of the mussel to be transported via shipping and recreational boating. Almost all waterbodies in Ontario that are downstream of established colonies or which can be reached through boating are vulnerable to invasion. However, there are ecological requirements (derived from European literature) which limit successful zebra mussel reproduction. Using data from over 6000 inland lakes in the province we have prepared maps which show the distribution of pH, calcium, and major access routes and indicate our estimated potential for success or failure of zebra mussel colonization. The utility of the maps is dependent on the validity of the ecological requirements for successful development of zebra mussel larvae, which were developed in Europe. There is a need to test the chemical requirements of the zebra mussel in North American waters. The inland waters at most risk of invasion by the zebra mussel are lakes and rivers of the Trent-Severn and Rideau Waterways.

Introduction

The zebra mussel (*Dreissena polymorpha*), a small bivalve mollusc native to Europe, is now well established in the Great Lakes system. Initial colonization may have occurred in 1986, probably from larvae discharged in ballast water (Griffiths et al. 1991). The mussel was first observed in Lake St. Clair in June, 1988 (Hebert et al. 1989) and in western Lake Erie in July, 1988 (Leach 1991). By November, 1990, the mussel had spread throughout Lake Erie, and through the Welland Canal and Niagara River into the western basin and south shore of Lake Ontario. Isolated populations have been found in the other Great Lakes as far west as Duluth, Minnesota and as far east as the St. Lawrence River at Cornwall, Ontario. Rapid dispersal downstream is aided by a high fecundity and a pelagic larval stage. Upstream dispersion is mainly due to shipping and boating with the zebra mussel carried either in ballast or attached to solid surfaces by byssal threads.

The zebra mussel is a serious pest in Europe (Clarke 1952) and is rapidly becoming one in North America. In high densities, it presents major problems for both civil engineering structures and for the ecology of infested water bodies. One of the most harmful impacts is the colonization of intake cribs and pipes serving water treatment plants, power generating stations and industries (Griffiths et al. 1989). Many installations on Lake Erie and Lake St. Clair have already been colonized to the point where flows have been restricted (Griffiths et al 1989).

As an efficient filter feeder, the zebra mussel is capable of removing large amounts of seston from the water (Hebert et al. 1991; Kryger and Riisgård 1988). In western Lake Erie, mean Secchi disc transparencies for the May-to-November period almost doubled between 1988 and 1989 (Leach 1991). In some areas of Europe, the processing of seston by *Dreissena polymorpha* is considered beneficial in water quality management (Reeders and Biji de Vaate 1990). However, there is concern in North America about the long-term effects of shifting so much organic matter from the pelagic to benthic zones. For example,

mean chlorophyll a for the May-to-November period declined 54 percent in the western basin of Lake Erie between 1988 and 1990 (Leach 1991). Concentrations of chlorophyll a are now in the one to two $\mu g \cdot L^{-1}$ range which classes the basin at the oligotrophic end of the trophic scale (Leach 1991). Effects of these dramatic changes in water clarity and energy distribution on invertebrate, aquatic plant and fish communities have yet to be determined.

Of further concern to fisheries managers is the rapid colonization of rocky reefs that are used for spawning by important commercial, sport and forage species of fishes. Although reef substrates have been completely altered by the infestation of mussels, adverse impacts on walleye (*Stizostedion vitreum vitreum*) have not been observed to date (Fitzsimmons et al. 1991). There was initial concern that egg survival could be affected by high amounts of organic matter being deposited on the shoals as a result of mussel fecal and pseudofecal production. Potential impacts if any, on fall spawners such as lake trout (*Salvelinus namaycush*) and lake whitefish (*Coregonus clupeaformis*) have yet to be assessed. Negative impacts of *Dreissena polymorpha* on native unionids have been observed in Lake St. Clair and Lake Erie (Mackie 1990; Schloesser and Kovalak 1991). The rich diversity of the unionid community in these lakes may be reduced through extinctions of some species.

The Laurentian Great Lakes are by no means the only aquatic resource at risk in Ontario due to infestation by the zebra mussel. In addition to a share of four of the Great Lakes, Ontario is estimated to have approximately 262,000 lakes with a surface area greater than 1 ha (Cox 1978). The numbers and lengths of rivers and streams in the province has not been determined, so the extent of potential disruption of lotic ecosystems cannot be quantified. The potential for the spread of zebra mussels to these inland waters is of great concern to managers and municipal, industrial, and recreational users of these resources. Although North American experience to date has been limited to large lakes, European information (Mackie et al. 1989) indicates that smaller water bodies on the scale of many of Ontario's inland lakes are vulnerable to impacts from the mussel.

Strayer (1991) has determined an area of potential invasion of the zebra mussel for North America based primarily on its thermal requirements as inferred from its distribution in Europe. However, there are chemical as well as thermal limits to the distribution of the zebra mussel. Sprung (1987) evaluated the chemical requirements for zebra mussel and determined that the larvae had very low survival rates at low pH and calcium concentrations.

Fortunately, the past decade has seen the development of extensive data bases of lake water chemistry, stimulated primarily by a need to assess the extent of lake acidification. Here, we use the Ontario Acid Sensitivity Data Base on over 6000 inland lakes in the province, along with maps of bedrock and surficial geology, and maps of major highways to construct maps of the relative probability of zebra mussel invasion to inland waters of the province. We also discuss problems of interpretation and extrapolation associated with current understanding of the chemical requirements of the zebra mussel. These preliminary maps may assist in focusing efforts to control the spread of the zebra mussel.

Methods

Water Chemistry Mapping

Sprung (1987) assessed the chemical requirements of zebra mussel reproduction. He reported no successful development of zebra mussel larvae at pH less than 7.4. Minimal survival of larvae was observed at calcium concentrations of 12 $mg \cdot L^{-1}$, and from data presented in Sprung's paper, 10% total rearing success of zebra mussel can be inferred to occur at approximately 20 $mg \cdot L^{-1}$. Based on these observations, critical water chemistry values were defined as pH of 7.4, and two calcium values: 12 $mg \cdot L^{-1}$ and 20 $mg \cdot L^{-1}$. These calcium concentrations may prove to overestimate the area of the resource at risk due to zebra mussle invasion, since a recent review of the distribution of the mussel in European

lakes showed that it was confined to lakes with a calcium concentration greater than 28 $mg.L^{-1}$ (Ramcharan et al. 1991).

Zebra mussel larval survival was qualitatively classified as 'unlikely' if measured or mapped lake pH was less than 7.4. In areas of the province where mapped or inferred water chemistry had pH $\geq$ 7.4 and calcium concentrations between 12 and 20 $mg \cdot L^{-1}$, survival likelihood was termed 'possible'. If measured or inferred pH was greater than 7.4, and measured or inferred calcium concentration was greater than 20 $mg \cdot L^{-1}$, survival likelihood was classified 'probable'.

The water chemistry data base has been described in detail elsewhere (Neary et al. 1990). It is composed primarily of water chemistry data from a single sample from a mid-lake location, with winter being the most common sampling time. One of the requirements for the inclusion of data in the data base was that a measure of Gran alkalinity was available for the lake. There were considerable amounts of data also available on lakes that included fixed-endpoint alkalinity measurements, frequently with calcium data as well (Ontario Ministry of the Environment 1980, 1981, 1982, 1983) . For the purposes of this mapping exercise, these lakes were also included. At higher alkalinity concentrations, the difference between fixed-endpoint and Gran alkalinity was felt to be insignificant.

A total of 3950 lakes had calcium measurements. Since calcium is the major cation in solution in Ontario lakes, it is highly correlated with conductivity (Figure 1). This regression was used to estimate the calcium concentration on a further 2201 lakes with pH and conductivity data, but where calcium data were missing. This gave us a data base of 6151 lakes with pH measurements and either measured or estimated calcium concentrations. The location of these lakes is shown in Figure 2. The lake water chemistry data were mapped using a SPANS geographic information system. The point data were converted to areas with a technique called potential mapping (TYDAC, 1988). The assumptions inherent in potential mapping are that a point attribute (in this case lake pH or lake calcium) is related to the attribute of other, unsampled, areas around it. The amount of interaction

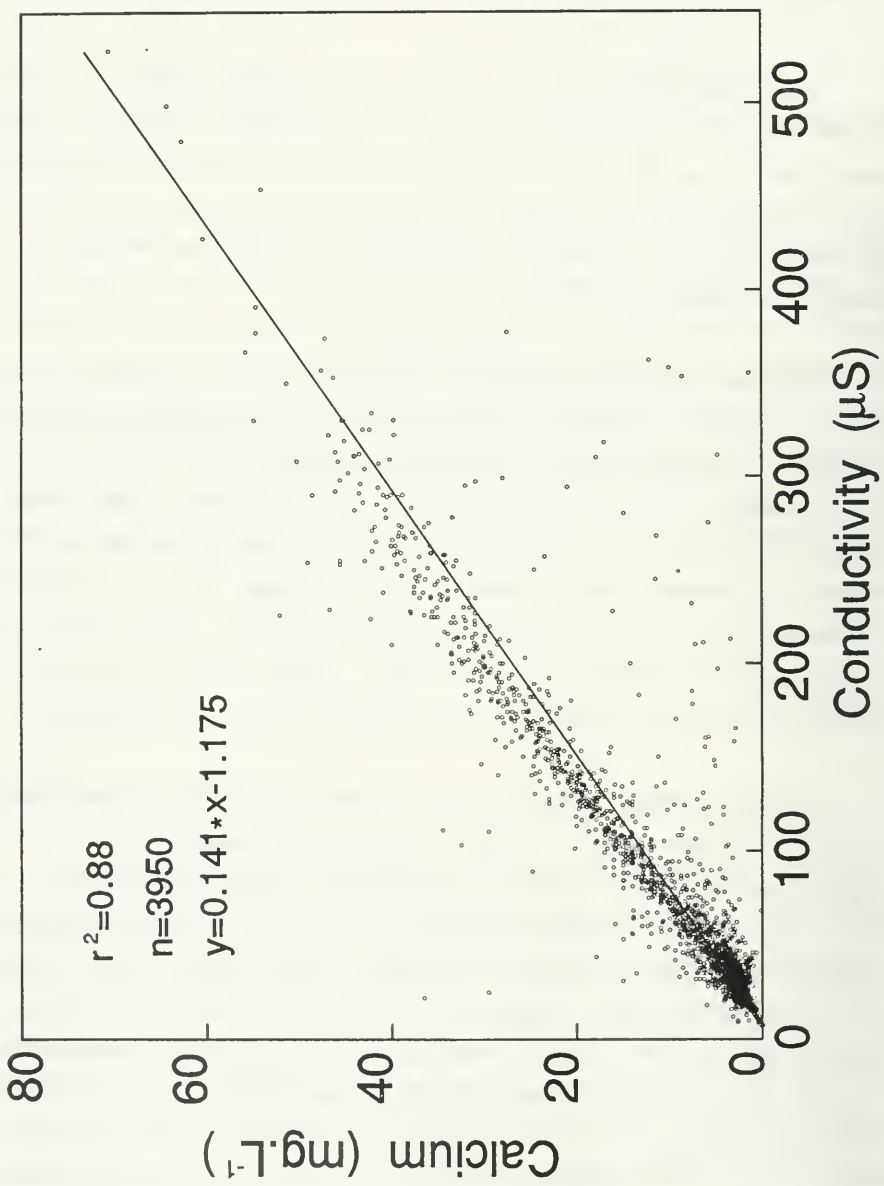

Figure 1: The relationship between conductivity and calcium concentration in Ontario Lakes.

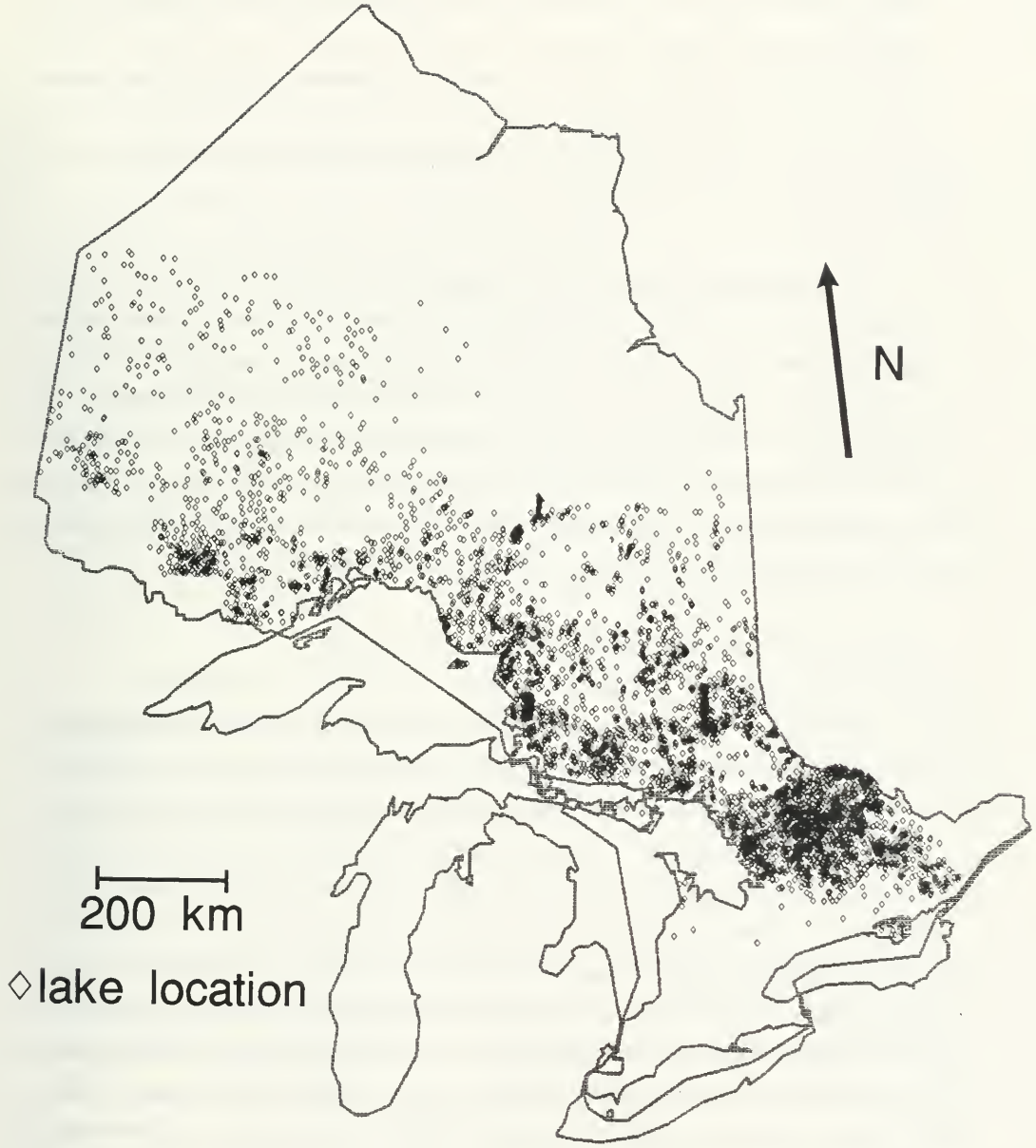

Figure 2: Location of lakes in Ontario with measured pH and measured or calculated calcium.

between points decreases with increasing distance between the points. In constructing pH and calcium water chemistry maps, each observation was given an inner radius of 500 m where neighbouring observations could not override the measured value. Each observation was then allowed an outer radius of 10 km. The value of the map for areas with no direct measurement was then calculated as the weighted sum of all points with influence on the map element.

There are large areas of the province where there were no observations (Figure 2). In some areas (e.g., southwestern Ontario), this is due to low densities of lakes. Other areas, particularly much of Northern Ontario, are poorly sampled due to access difficulties. The lakes were sampled primarily because of interest in assessing the impact of acid deposition, and northern Ontario receives much less acid deposition than the southern portions of the province. Lake acidification of softwater lakes in Ontario is directly correlated to the amount of acid deposition (Neary and Dillon 1988) and sampling effort was mostly directed to areas where acidification impacts were suspected.

Inferring Water Chemistry from Surficial and Bedrock Geology

The calcium concentration of lakewater is primarily determined by the geology of the lake catchment. Lakes in areas with significant amounts of limestone or calcareous till will have higher calcium concentrations than those in areas dominated by granites or gneisses. Cowell (1986) produced maps of Ontario classifying the province into terrain types according to the capability of soils and rock in the area to neutralize acid deposition. This formed the basis for a national assessment of the potential of soils and bedrock to reduce acidity (Environment Canada 1988). The conditions which favour the survival of zebra mussels are the opposite of the conditions which render lakes susceptible to acidification. The use of the maps which predict the susceptibility of lakes to acidification was evaluated as a means of predicting surface water conditions which may be suitable for zebra mussel survival. Lakes were grouped according to the major terrain type of these maps, and the resulting classification was assessed as to its ability to predict pH and calcium concentration, based

on measurements from the data base.

Evaluating Variability in the Chemical Data

One of the problems with mapping suitability based on one or more chemical criteria is the fact that water chemistry is variable both seasonally and annually. This is illustrated with a series of water chemistry data from Glen Lake, a small (16.3 ha) hardwater lake in central Ontario (45° 08'N, 79° 01'W). Glen Lake is not typical of lakes on the Precambrian Shield area of Ontario, and owes its high calcium content and high pH to its situation on a localized dolomitic marble deposit. Of a number of lakes monitored regularly for a number of programs by staff at the Dorset Research Centre, it is the highest in pH and calcium, and represents a lake with conditions suitable for zebra mussel survival. This lake has been sampled bi-monthly during the ice free season each year since 1978 (Girard and Reid 1990), as well as twice annually under ice cover. The seasonaland long-term trends were plotted using seasonally detrended robust locally weighted regression methods developed by Bodo (1989).

The majority of data in the Ontario Acid Sensitivity Database is from single grab samples either through the ice or from the epilimnion. The Glen Lake data are from sampling in the centre of the lake in the epilimnion during stratification, or a volume weighted water column sample during the period when the lake is not stratified.

Assessing Accessibility

In addition to suitable water conditions, ease of access will likely influence the probability of zebra mussel invasion. The primary vector for dispersal of zebra mussel in inland waters is thought to be boats or bait buckets. The inland waters of Ontario at highest risk are those with direct boat access to the Great Lakes. In Europe, canals have enhanced the dispersal of the mussel (see Mackie et al. 1989, for a review of European dispersal mechanisms). Two canal systems (the Trent-Severn and the Rideau) are undoubtedly at

highest risk of invasion. In November, 1990, zebra mussels were found on the hull of a boat in the Rideau Canal near Ottawa, Ontario. Boats which are transported over land from infested waters form another potential dispersal vector because zebra mussel larvae can potentially survive in boat livewells or bilges, and adults can survive out of water for several days depending on temperature and humidity. Boat related dispersal vectors require road access to lakes. A further classification of likelihood of zebra mussel invasion ('very probable') was assigned to areas where water chemistry requirements were met and access (defined as being within 10 km of a major highway) was good.

Results

Maps of Water Chemistry

Maps of calcium with three classifications ([Ca] < 12 $mg \cdot L^{-1}$, 12 ≥ [Ca] < 20 $mg \cdot L^{-1}$, and [Ca] ≥ 20 $mg \cdot L^{-1}$) were produced for Ontario. Maps with two pH classifications were then imposed on the calcium maps to produce a map with three water chemistry classifications: (a) pH < 7.4, (b) pH ≥ 7.4 and Ca ≥ 12 $mg \cdot L^{-1}$, and (c) pH ≥ 7.4 and Ca ≥ 20 $mg \cdot L^{-1}$ (Figure 3). Generally, the map of areas of high pH aligned almost exactly with areas of high calcium. The only exception was a relatively small area in the vicinity of Sudbury, Ontario. This area has received large amounts of sulphur loading from smelters operating in the area, and had lakes with high calcium concentrations coupled with relatively low pH. The different classes on Figure 3 represent areas where measured water chemistry in inland lakes are suitable (pH≥7.4 and Ca≥12 $mg.L^{-1}$) or unsuitable (pH<7.4 or Ca<12 $mg.L^{-1}$) for zebra mussel larvae survival, based on survival criteria inferred from Sprung's (1987) assessment.

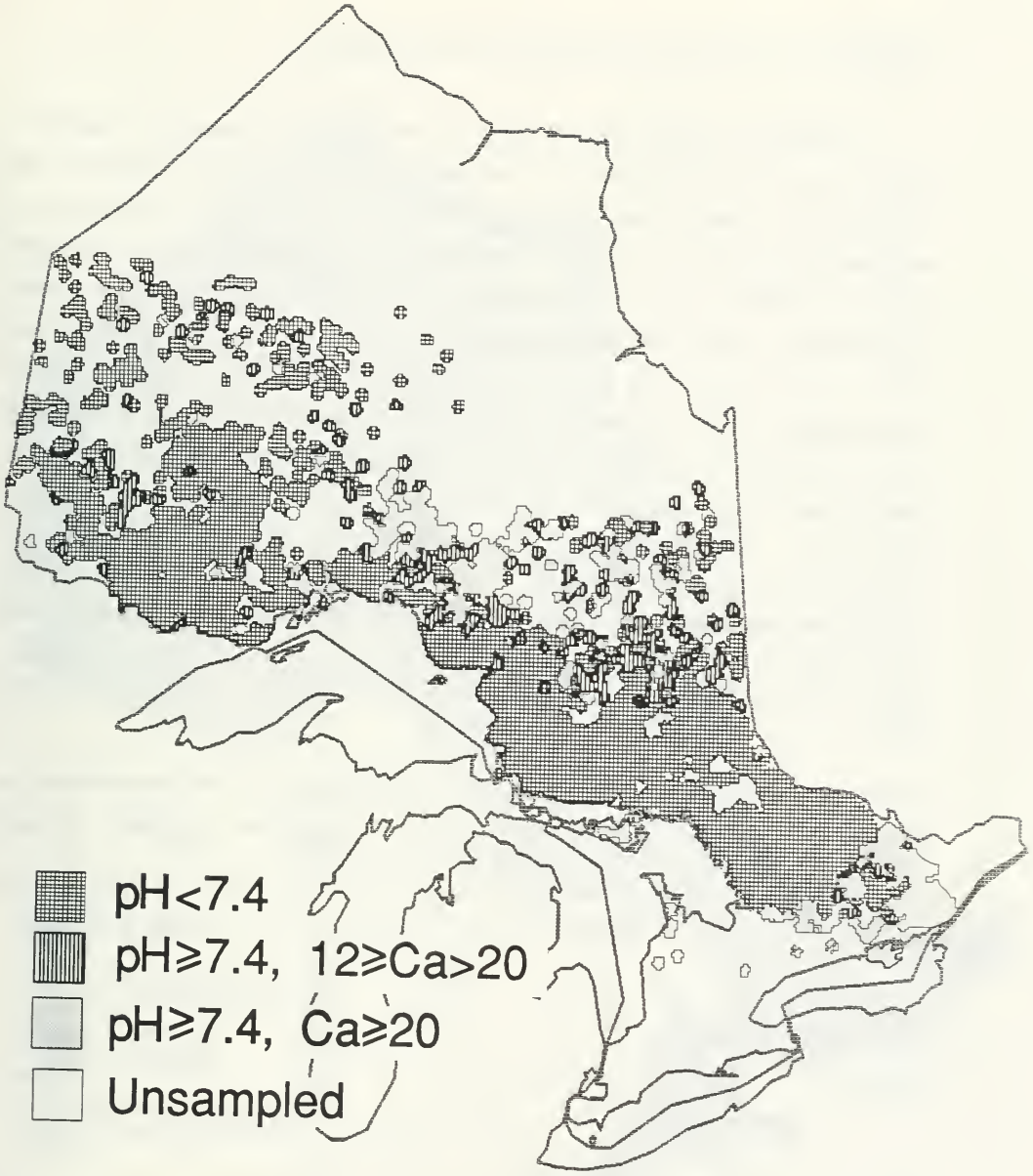

Figure 3: Areas of Ontario with measured or calculated water chemistry of varying suitability for zebra mussel larvae survival.

Grouping lake calcium and pH by the surficial and bedrock geological types yielded two useful classifications (Table 1). Grouping was done on digitized versions of the 1:1000000 maps published by Cowell (1986). The resolution of these maps cannot be adequately reproduced at the scale of a normal page, so the lower resolution (1:7500000) surficial and bedrock geology maps published by Environment Canada (1988) are shown here (Figure 4). Areas classified as having a low potential to reduce acid deposition had 15% of lakes with pH ≥ 7.4 and 13.3% of lakes with measured or estimated calcium concentrations ≥ 12 $mg \cdot L^{-1}$. Areas with a high potential to reduce acid deposition had 75% of lakes with pH ≥ 7.4 and 81% of lakes with measured or estimated calcium ≥ 12 $mg \cdot L^{-1}$. Lakes in the other two geological classifications had pH and calcium distributions which bracketed the critical pH and calcium values, and had error terms which made them unacceptable for classification.

Table 1: pH and calcium characteristics of Ontario lakes classified according to the potential of soils and bedrock in their drainage areas to reduce acidity (from Environment Canada 1988).

Geological Class[1]	N	Median pH	% pH≥7.4 $mg \cdot L^{-1}$	Median Ca $mg \cdot L^{-1}$	% Ca≥12 $mg \cdot L^{-1}$	% Ca≥20
'Low'	4557	6.54	15.0	3.54	13.3	6.0
'Medium'	1138	7.08	35.4	7.66	33.4	19.7
'High'	399	7.80	74.9	20.6	81.0	61.1
'Organic'	53	7.50	58.5	11.9	56.6	32.0

[1] Potential of soils and bedrock to reduce acidity.

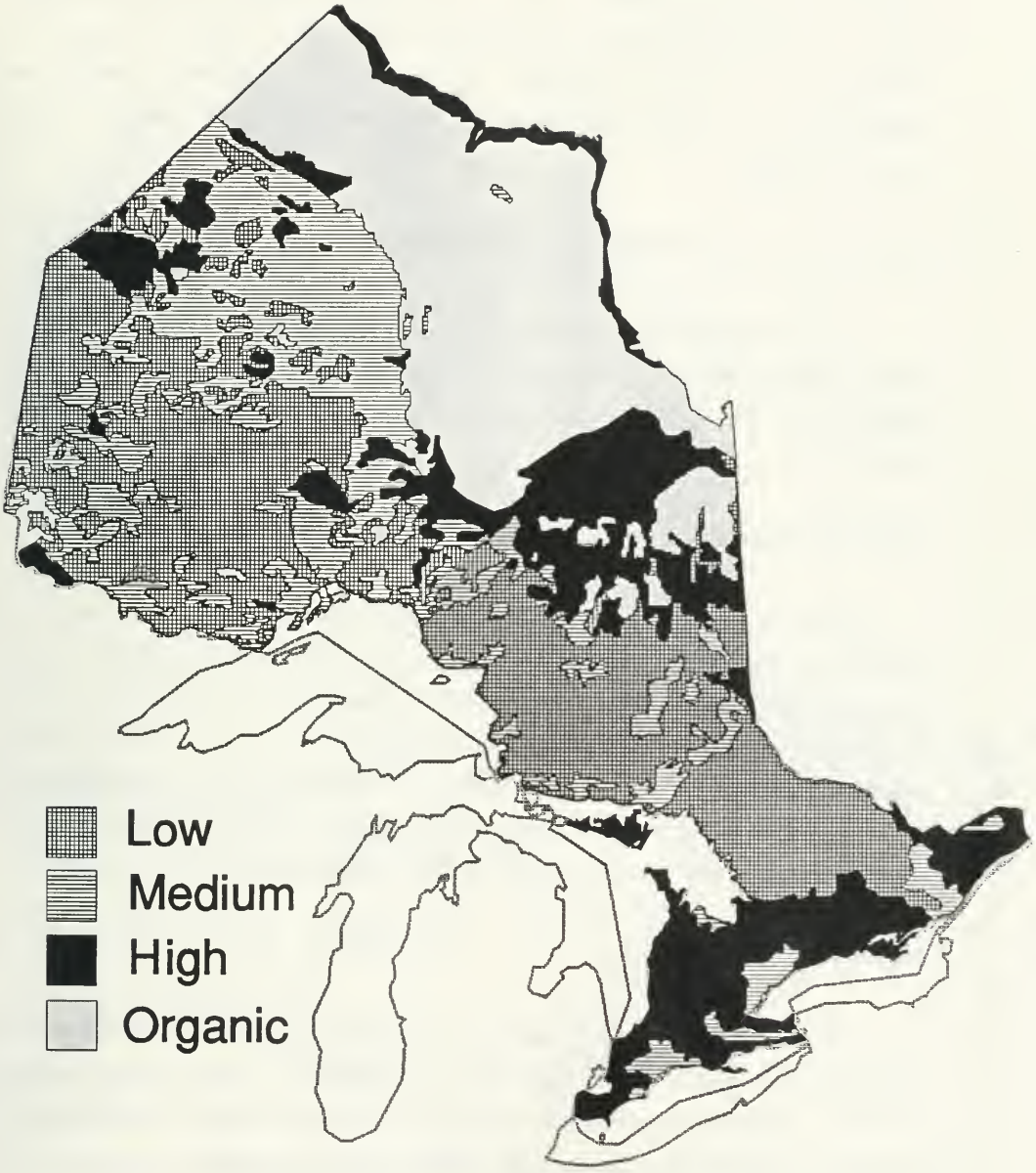

Figure 4: The potential of soils and bedrock to neutralize acidity (from Environment Canada, 1988).

The map of water chemistry (Figure 3) was superimposed on the two geology classes, and the result is shown as Figure 5. For this map, the measured water chemistry was given priority over the geological theme, and only the two classes considered to be useful for predicting water chemistry were used. Areas of the province where geology was inappropriate for predicting water chemistry (the 'medium' and 'organic' areas from Figure 4) were not assigned.

Seasonal and Annual Variability of pH and Calcium

The seasonal and long-term trends in the data series of pH and calcium from Glen Lake are shown in Figure 6. The strong seasonal variability of both parameters is evident. Seasonal fluctuations contributed 78.5 and 24.5 percent of total variability in pH and calcium respectively.

Zebra Mussel Invasion Probability Map

Maps of good road access were constructed by defining a corridor extending 10 km to either side of major highways of the province (Figure 7). The water chemistry map as extended by geological classification (Figure 5) was imposed on this access map, and areas where water chemistry was measured or predicted to be suitable for zebra mussel, and road access was good were defined as 'very probable' to be invaded by zebra mussels (Figure 8). Also shown on Figure 8 are two temperature isotherms, determined by Strayer (1991) to represent potential northern limits for the invasion of zebra mussels.

Discussion

The large database of water chemistry accumulated as part of the Acid Precipitation in Ontario Study proved extremely useful in classifying areas of known water chemistry according to published water chemistry requirements of the zebra mussel. Classifying lakes according to a combination of bedrock and surficial geology considerably extended the area

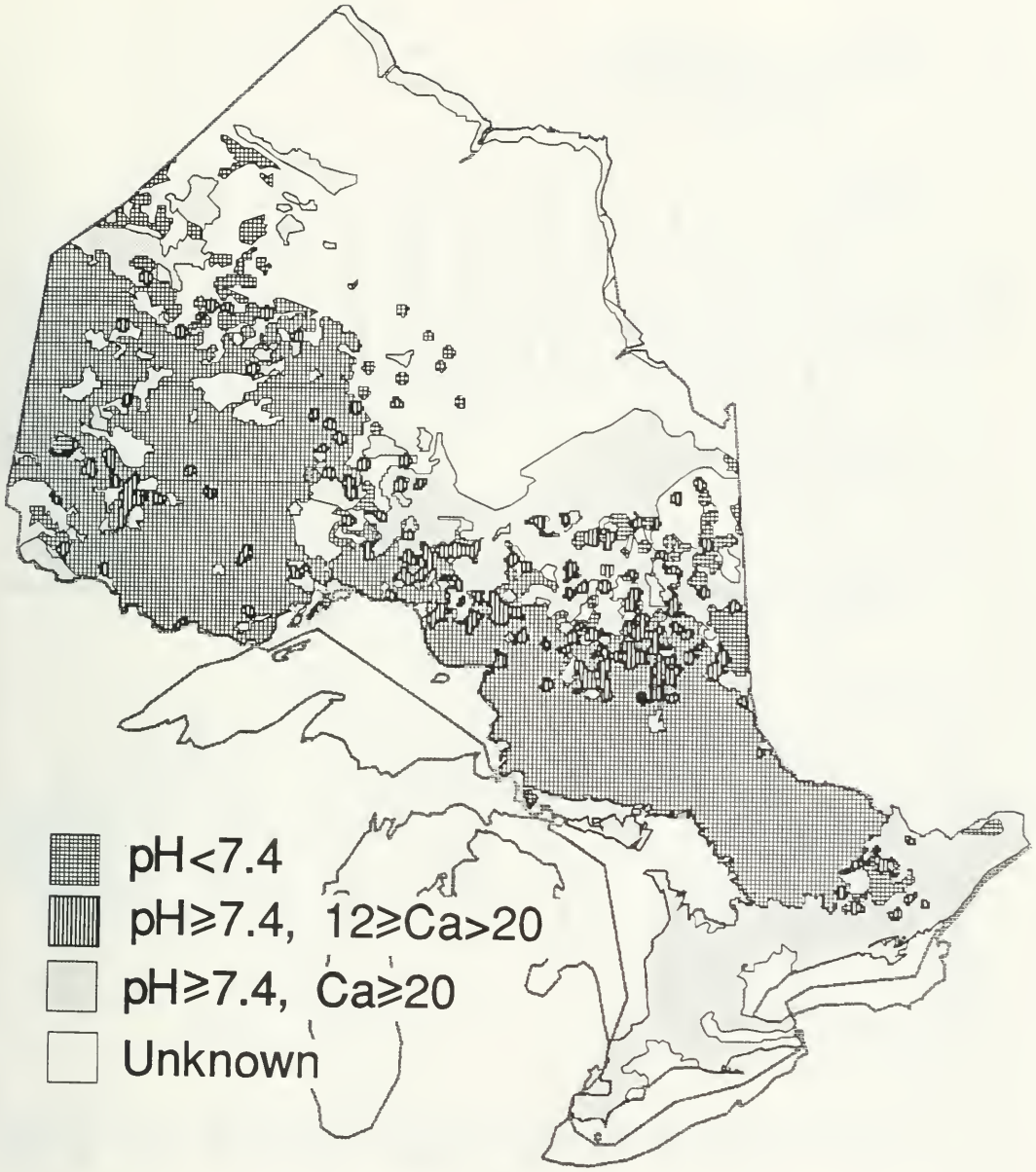

Figure 5: Combination of areas with measured or calculated water chemistry (Figure 3) with areas of low and high potential to reduce acidity (Figure 4) to produce conditions of varying suitability for zebra mussel larvae survival.

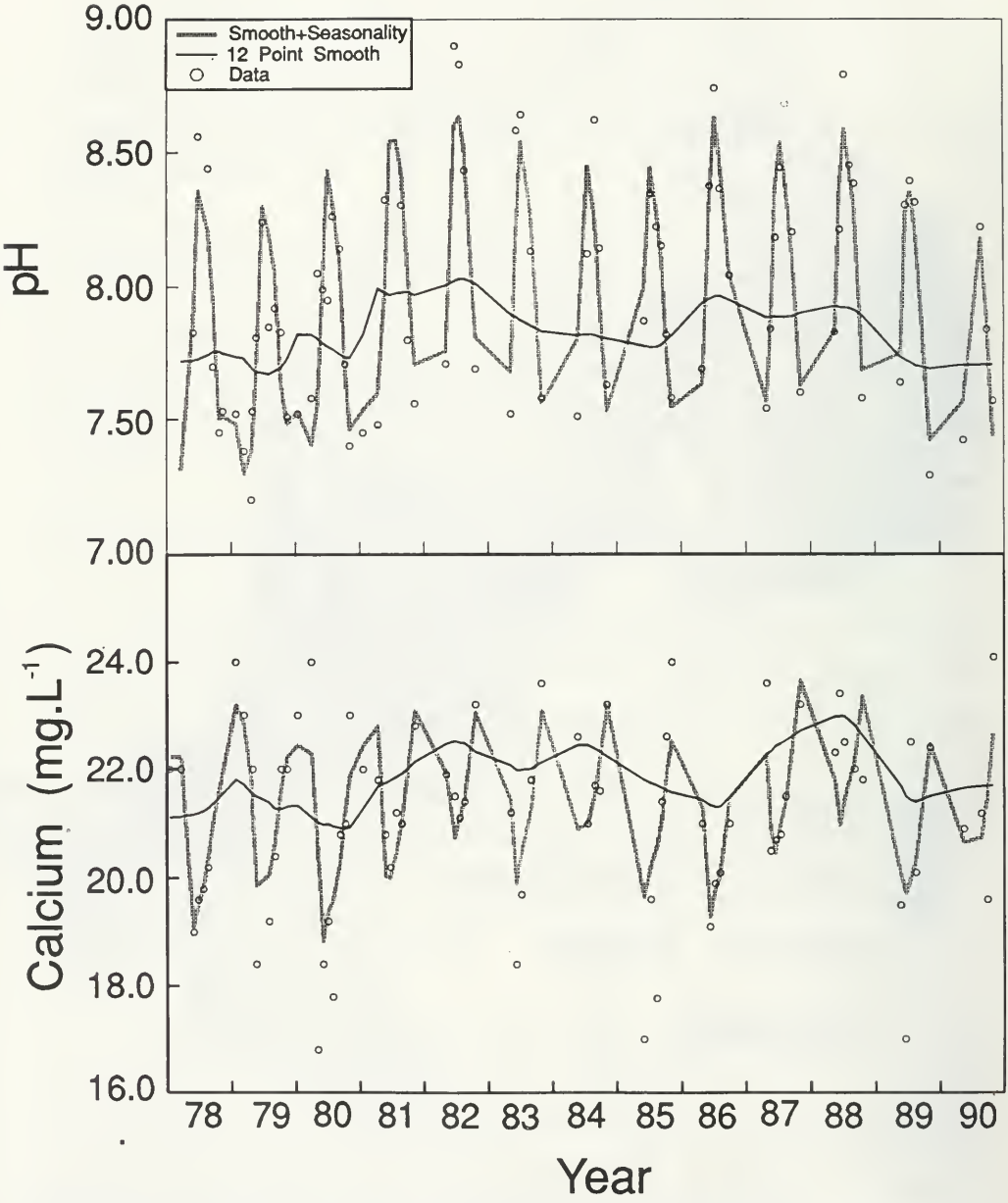

Figure 6: Annual and seasonal variability of pH and calcium in Glen Lake, Ontario, 1978 to 1990.

Figure 7: Map of areas with good road access from major highways in Ontario.

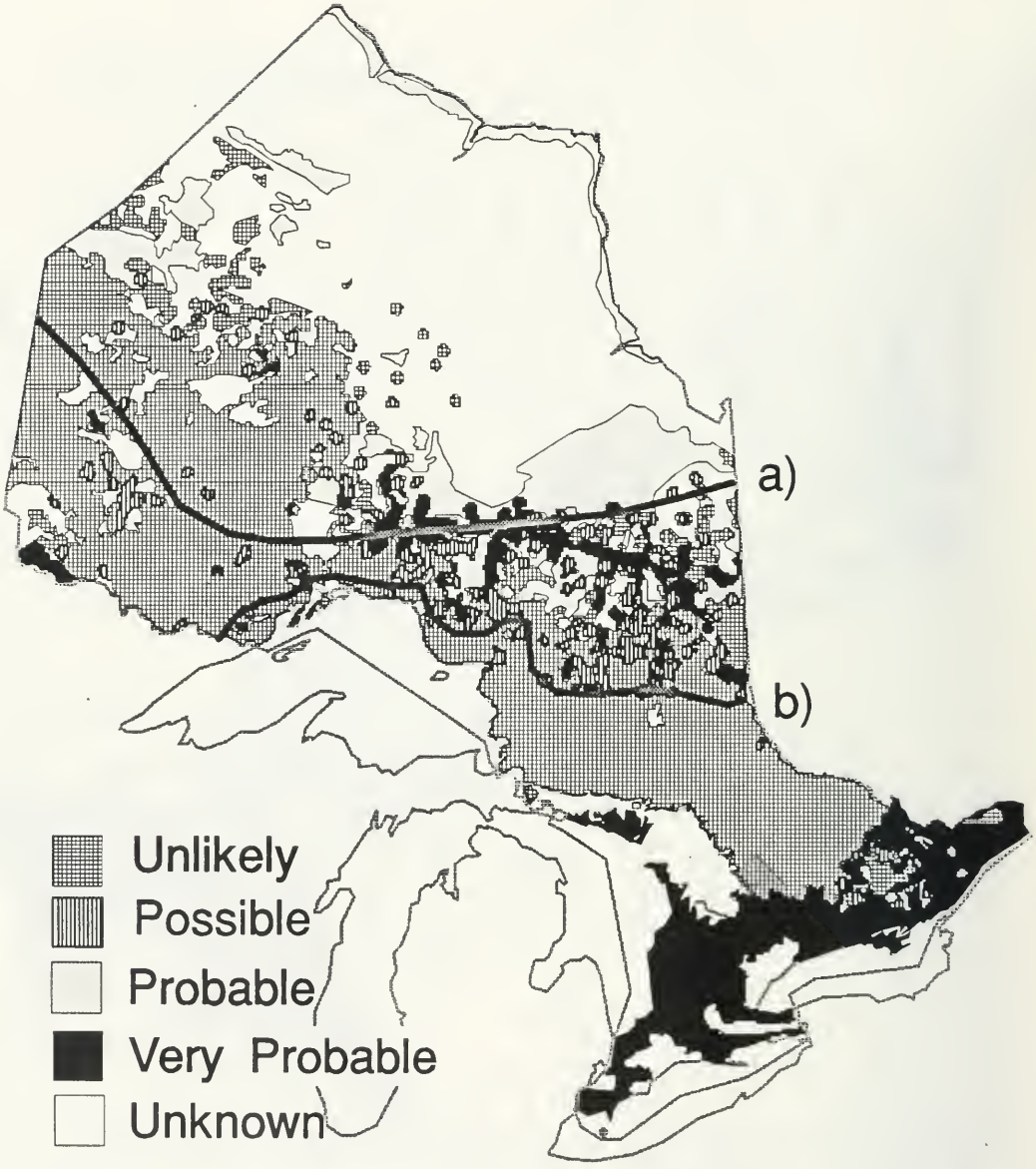

Figure 8: Map of Ontario showing the relative probability of zebra mussel invasion. Isotherms for a) mean annual temperature of 0°C and b) mean January temperature of -15°C are shown. These temperatures may represent the northern extent of the range of the zebra mussel (Strayer 1991).

of the province which could be mapped as having conditions likely to be suitable or unsuitable for zebra mussel invasion.

The use of corridors along major highways to assign a higher probability of zebra mussel infestation probably has more validity in sparsely populated areas of northern Ontario than in southern Ontario. The southern portion of the province has an excellent network of secondary roads which can provide good access to lakes and rivers, and which is not captured by the map. In northern Ontario, access in areas not close to major highways is considerably more limited, although some areas are accessible through secondary roads or logging roads. Fly-in fishing operations represent another potential vector for dispersal of zebra mussels which is not evaluated here.

The utility of these maps is strongly contingent on the validity of the chemical requirements for successful zebra mussel larval development which, to date, have been tested only in Europe. Sprung (1987) did not examine the survival of larvae at calcium levels between 12 and 0 $mg \cdot L^{-1}$, which is the range of calcium concentrations for the majority of Ontario lakes. The pH limitation of 7.4 is also problematic, since both pH and calcium concentrations are not static in a lake environment. Further, the pH limit of 7.4 was derived from a study where the zebra mussel was given no opportunity to acclimate to lower pH or calcium conditions.

Most of the data in the lake surveys represent subsurface 'grab' samples. The seasonal and annual data from Glen Lake cover the periods of the year when grab samples were taken. Clearly, pH and calcium undergo significant seasonal variations in lakes. Variations in the littoral area, where zebra mussel colonization would be most likely, could be significantly greater. pH, in particular, would fluctuate in the inshore areas, with decreases occurring in the spring associated with snowmelt and runoff from adjacent shorelands and increases occurring later in the summer associated with respiration. Glen Lake may not be typical of larger lakes, since it receives a large portion of its input from runoff from its local watershed. Biologists attempting to further define the chemical

requirements of the zebra mussel should bear in mind the variable nature of lake water chemistry. Limnologists attempting to classify lakes according to these or other water chemistry parameters should also attempt to address this type of variability.

The ecological problems associated with zebra mussel infestation are not a function of its mere presence, but are related to its abundance. Factors which will likely control its density (suitability of substrate, productivity, area of littoral zone) were not evaluated here. These data are not typically available for many of the lakes in Ontario.

The map presented here shows that there is a wide range of probability of invasion of the zebra mussel to inland lakes in Ontario. The likeliest systems to be invaded by the zebra mussel are lakes and rivers along two major waterway systems in southern Ontario, the Trent-Severn and the Rideau waterway systems. The lakes along these systems have excellent access both by road and by direct passage of boats from Lake Ontario and Georgian Bay on Lake Huron. They are characterized by high calcium concentrations and are meso- to eutrophic, providing an excellent food base for the mussel.

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